ULTRASONIC CHARACTERIZATION OF LASER ABLATION

J.A. Smith and K.L. Telschow

Idaho National Engineering Laboratory
EG&G Idaho Inc.
Idaho Falls, ID 83415-2209

INTRODUCTION

When a pulsed laser beam strikes the surface of an absorbing material, ultrasonic waves are generated due to thermoelastic expansion and, at higher laser power densities, ablation of the material. These sound generation mechanisms have been the subject of numerous theoretical [1-3] and experimental [4-6] studies and are now fairly well understood; several reviews have also been published [7-9]. In particular, it has been established that at low power densities the thermoelastic mechanism is well described by a surface center of expansion [1]. This mechanism produces a characteristic waveform whose amplitude is proportional to the energy absorbed from the laser pulse and also dependent on the thermal and elastic properties of the material [1-2]. At higher power densities the melting point of the material is reached, and eventually vaporization of the material takes place [5]. Rapid vaporization leads to ablation of material. Significant ablation occurs only during the laser pulse at power densities near the ablation onset threshold, creating an ultrasonic excitation source with the same time dependence as the laser pulse. At higher laser power densities the ablation process continues after the laser pulse and eventually the ultrasonic source changes from pulse to step like in time dependence [5,9]. In this region plasma absorption also plays a significant role.

The ablation ultrasonic source can be described by a point normal force acting on the material surface. For laser power densities near the ablation onset, the time dependence of the source is that of the laser pulse. The resultant waveform recorded on epicenter (source and detector collinear) has a sharp peak determined by the momentum impulse delivered to the material by the ablation process. Particularly in the near ablation onset region, this ultrasonic displacement peak can be used to characterize the ablation process occurring at the material surface. The onset power density for ablation and subsequent ablation dependence on power density are material dependent [10] and thought to be a function of the heat capacity and thermal conductivity of the material [9,10]. With this in mind, it is possible that these ablation signals could be used to characterize material microstructures, and perhaps material mechanical properties such as hardness, through microstructural changes of the material thermal parameters. This paper explores this question for samples of Type 304 stainless steel with microstructures controlled through work hardening and annealing.

EXPERIMENT AND PROCEDURE

The experiment consists of recording the ultrasonic displacement signals (on epicenter) at increasing levels of the source laser pulse energy. The source was 1064 nm radiation from a Nd:YAG pulsed laser, 15 ns pulse width, focused to a 3 mm diameter spot size on the sample surface, with pulse energies from 30 to 200 mJ/pulse at 10 Hz repetition rate. The ultrasonic waveforms were recorded with a laser heterodyne displacement detector [11]. A sample holder allowed removal and replacement of samples with excellent reproducibility. The laser pulse energy was controlled by passing the beam through a series of glass microscope slides to provide distinct, reproducible, pulse energies. This unit employed pairs of slides oriented at ±1 degree off normal to the beam to avoid displacing the beam upon insertion and removal.

A typical recorded waveform is shown in Fig. 1, which includes both thermoelastic and ablation contributions. This waveform is for the maximum laser pulse energy used. Only the sharp, first arrival peak shown in Fig. 1 was used as it is due primarily to the momentum impulse of ablation. It can be shown that for this part of the waveform the displacement is given by $U(t) = (I/\pi\mu h)f(t-h/C_L)$, where I is the ablation impulse, μ the shear modulus, h the plate thickness, f(t) the laser pulse shape, and C_L the longitudinal wave speed [6]. It is assumed that ablation is described by a normal point force at the surface (near ablation onset region).

Four 10 mm thick samples were cut from 25 mm diameter Type 304 stainless steel bar stock. Their hardness measured 300±5 DPH (100 g load). Two samples were shock hardened using a sheet explosive to

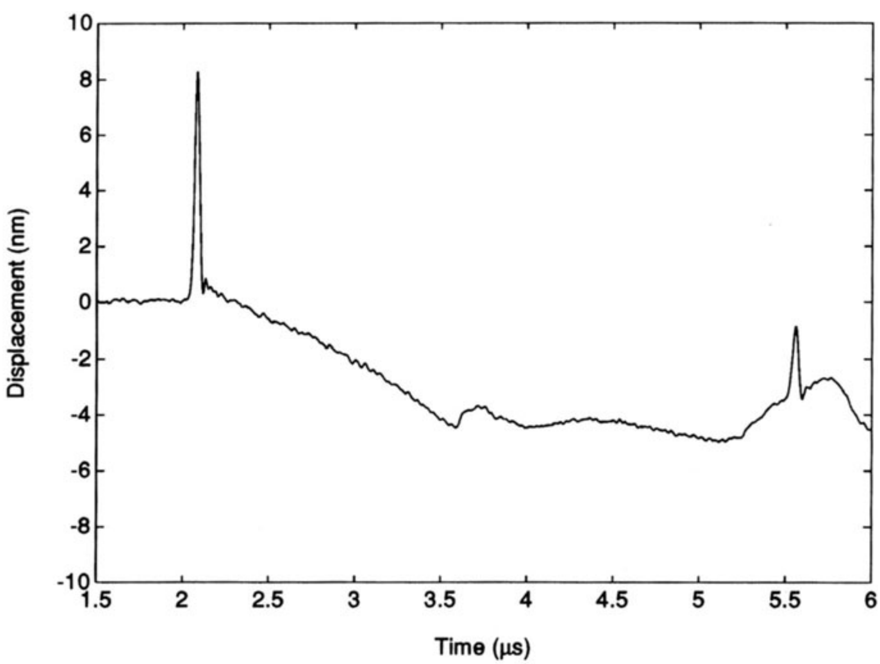

Fig. 1. Signal from ablation and thermoelastic ultrasonic displacement recorded on epicenter for the "as-received" sample. Sample thickness, 10.0 mm; incident laser pulse energy, 200 mJ/pulse.

increase the work hardening and hardness. These samples then exhibited hardness of 280±6 DPH. Apparently, the as-received material was already considerably work hardened and the shocking did little to the microstructure. Optical micrographs indicated that the as-received material had well defined grain boundaries and slip bands; the grain size was about 30 μm. The shocked material was similar, but the grain boundaries were indistinguishable.

Ablation signals were recorded from these samples. The samples were subsequently annealed at 1065°C for 15 min and cooled in air at room temperature. This procedure eliminated the slip bands and increased the grain size to about 60 μm. The as-received and shocked samples were very similar in microstructure after annealing, and their hardnesses were 155±7 and 160±9 DPH respectively. After surface polishing (0.3 μm alumina powder), these samples were ablation tested as before. The ablation signals were recorded as a function of laser pulse power density, with an average of over 100 shots made at each density level. All samples were ablated prior to measurement to ensure a fresh material surface was exposed.

RESULTS AND DISCUSSION

Figure 2 shows typical waveforms recorded at the highest power density used for each of the four sample treatments. The results for the as-received and shocked samples were nearly identical; after annealing both samples also showed nearly identical results. However, there is considerable difference between the annealed and unannealed samples. Basically, the annealed samples exhibited a 30 to 40% decrease in signal amplitude as well as pulse broadening. Some of this decrease is due to increased ultrasonic scattering from the larger grains in the annealed

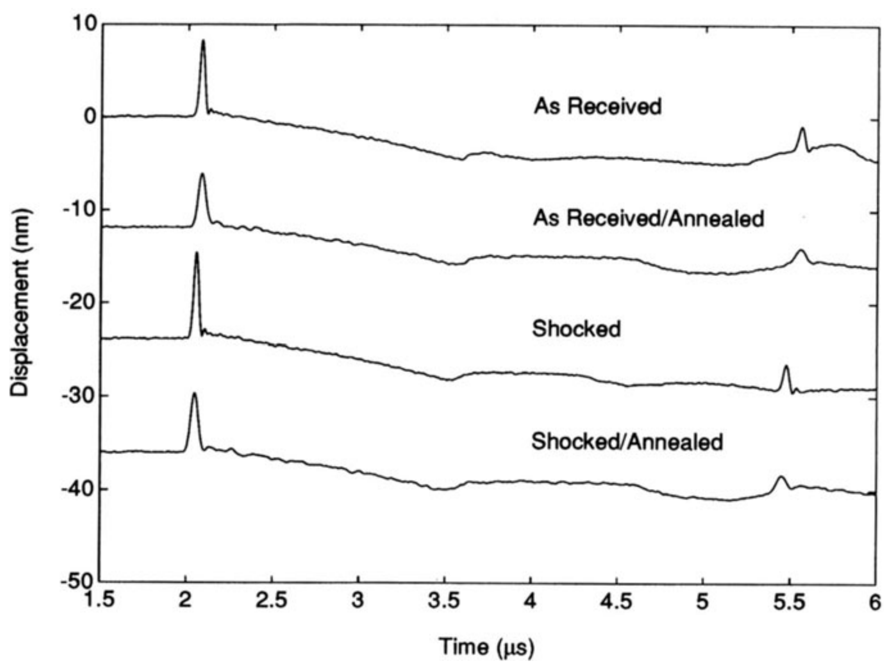

Fig. 2. Signals recorded for four samples before and after annealing. Incident laser pulse energy, 200 mJ/pulse.

samples. The magnitude of this effect can be determined from the second echo response, also shown in Fig. 2. Calculations indicate that at most 10% of the signal decrease between the work hardened and annealed samples can be accounted for by attenuation.

Measurements of the thermoelastic signals recorded at low power density from all four sample types are shown in Fig. 3. Thermoelastic signal amplitudes are known to be directly proportional to the energy absorbed in the material with each pulse and to be independent of the material's thermal conductivity [1]. The measured values coincide very well, which indicates that there is no change in optical reflectivity between samples. This confirms that the pulse energy absorbed for each sample was the same, at least up to levels where the material begins to melt. It is concluded that the difference in microstructure between the unannealed and annealed samples produced the significant decrease in the material ablation signal peak. The ablation signal peak amplitudes are plotted in Fig. 4 as a function of the incident laser pulse power density for the four sample types. Again, similar results are observed for the two work-hardened samples and similar, lower, results for the annealed samples. These data are presented on a log-log plot in Fig. 5, which shows that the results scale roughly as the square of the laser power density as is expected for ablation without the presence of a significant plasma [12].

CONCLUSIONS

The results of this study indicate that the onset of ablation and the dependence of ablation on incident pulse power density are functions of the material microstructure. A definite change in the ablation

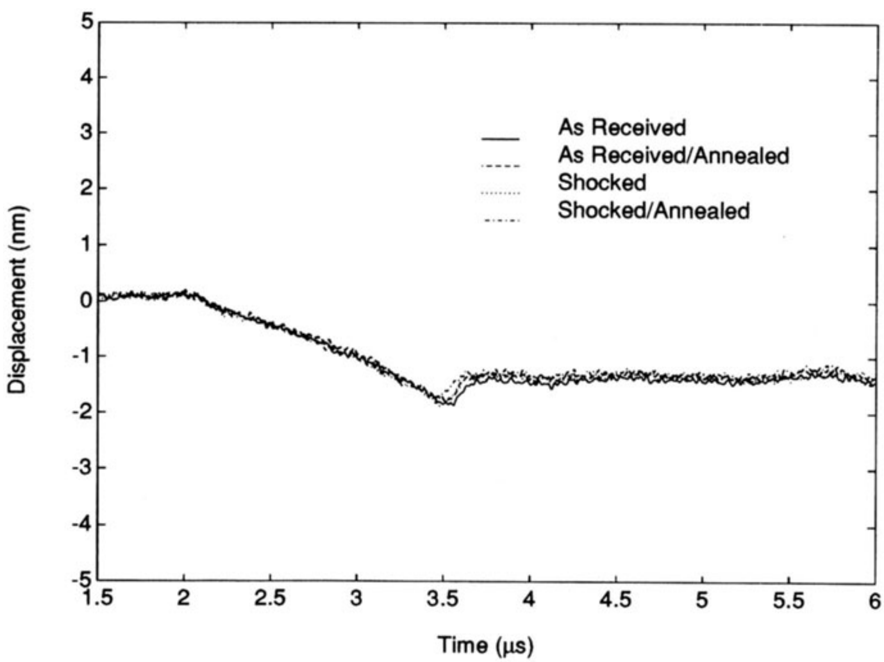

Fig. 3. Thermoelastic signals recorded at 30 mJ/pulse incident pulse energy for all four samples.

signals between the work hardened and annealed samples of stainless steel was observed that cannot be attributed to attenuation or changes in material optical reflectivity. At this time one can only speculate as to the origin of the microstructure dependence. It is possible that annealing increased the material thermal conductivity, so that a larger laser pulse power density is required to reach high enough temperatures for significant ablation to occur. This will be investigated with conductivity measurements. Another hypothesis is that in the unannealed samples the laser pulse releases stored residual stress due to work hardening and enhances the ultrasonic generation. In any case, these results indicate that it may be fruitful to pursue this type of measurement as a means of detecting local microstructural changes that affect the hardness of materials.

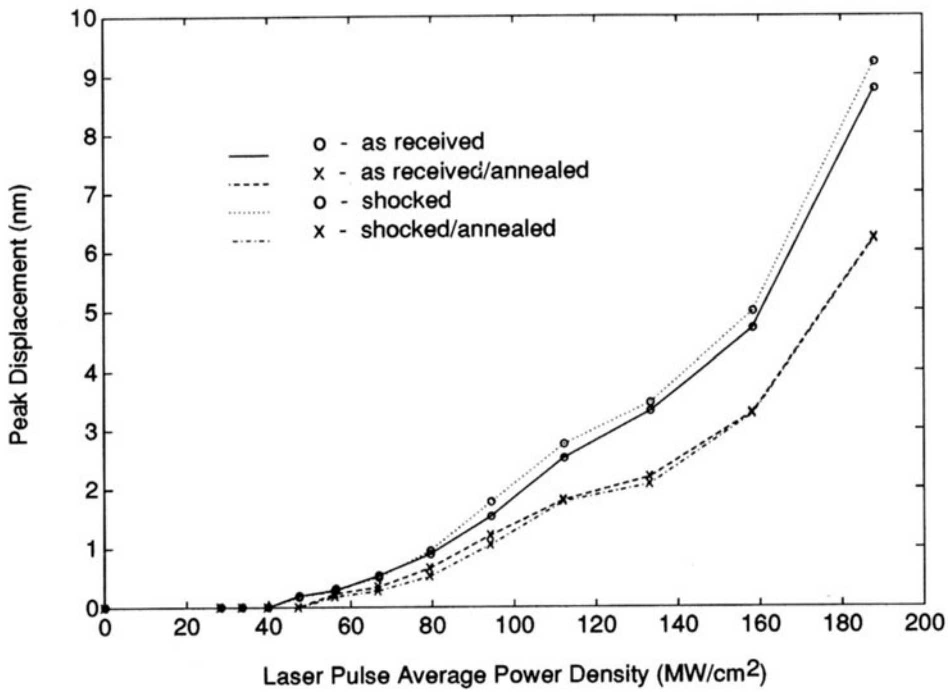

Fig. 4. Ablation impulse signal amplitude vs. incident laser pulse power density.

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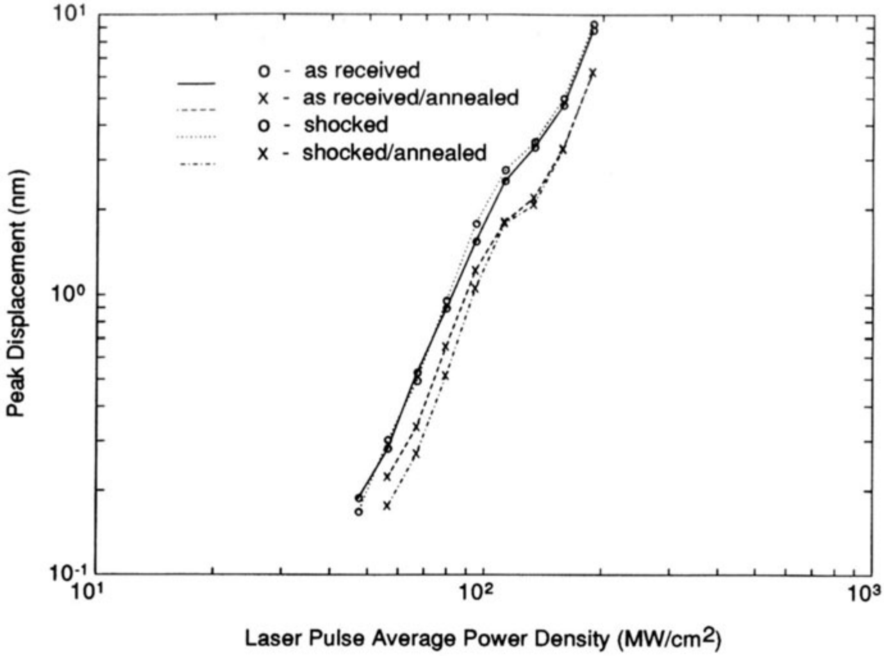

Fig. 5. Same data as in Fig. 4 replotted to show approximate dependence of the ablation signal on the square of the incident laser pulse power density.

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12. Ibid. ref. 9, page 245.